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Automatic Recording Equipment for Use in Energy Metabolism Studies with Dairy Cattle 1/

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Energy balance studies with large animals by means of open-circuit indirect calorimetry require an exact knowledge of total intake of feeds and oxygen and total excretion of fecal and urinary constituents, carbon dioxide and methane. The quantitative measurement of gaseous exchange requires the measurement of the volume of the exhaust gas from a respiration chamber and correcting it for changes in temperature, barometric pressure and relative humidity. The conventional means of obtaining this data has necessitated the presence of an operator 24 hours a day to read the gas meters, the wet and dry bulb thermometers and mercurial barometer.

One of the major reasons that extensive studies on the energy metabolism of cattle have not been conducted in the past has been the excessive amount of labor required in collecting and analyzing the data. The extreme slowness in which data were accumulated from respiration trials and the excessive cost of equipment also contributed toward discouraging individual research workers as well as research and educational institutions from engaging in this field of research. The use of automatic recording equipment to collect data and electronic computers to make the necessary computations would not only reduce the labor requirement for conducting respiration trials, but in many cases could result in greater accuracy than could be obtained by manual means. The immense number of observations and computations involved in each experiment are subject to human error which could be avoided by means of automation.

Six open-circuit (Pettenkofer) respiration chambers for mature dairy cattle have been constructed in the Energy Metabolism Laboratory, Nutrition and Physiology Section, Dairy Cattle Research Branch, Animal Husbandry Research Division, Agricultural Research Center, U.S.D.A., Beltsville, Maryland. Automatic instrumentation to record at regular intervals the data required for the measurement of respiratory exchange has been developed, installed and calibrated. The equipment consists of various sensing elements, a strip chart multipoint recording potentiometer, a shaft position encoder, control chassis, an automatic typewriter, IBM printing card punch, and IBM-APR console. These components are described in detail below.

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IBM-APR System - The IBM-APR (International Business Machines - Automatic Production Recording) system consists of a console (Model 9600) containing a programmer, commutator clock, 2 counter sections, an elapsed timer, 2 remote control units, a console printer (Automatic Typewriter 510) and printing card punch (Model 520). The system was designed to record and identify various parameters required in measuring the energy metabolism of dairy cattle. The system operates on a time basis, with the record period being 0.10 hour (6 minutes), but the interval may be changed to shorter or longer periods if desired. Control of the readout is furnished by the commutator clock. At the end of each six-minute period, all parameters are recorded simultaneously on a typewritten record and as a punched card and all counters are reset. The information recorded each time for each of the chambers, and the order in which they are typed and punched, is as follows:

1. Respiration chamber number
2. Time of day in hours and hundredths of hours
3. Date as month, day and year
4. Operator number
5. Ventilation recording unit number
6. Animal number
7. Period number
8. Animal weight in kilograms
9. Trial number
10. Experiment number

11. Number of animal position changes within the 6-minute period
12. Elapsed animal standing time within the 6-minute period
13. Volume of exhaust gas from meter No. 1 measured as number of complete revolutions of the bellows shaft of the gas meter
14. Volume of exhaust gas from meter No. 2 measured as number of complete revolutions of the bellows shaft of the second gas meter

15. Index number from the recording potentiometer (Recorder Point #1)
16. Barometric pressure of the room (Recorder Point #2)
17. Relative humidity of the chamber (Recorder Point #3 or #4)
18. Relative humidity of the exhaust gas (Recorder Point #5 or #6)
19. Temperature (°C) of the chamber (Recorder Point #7 or #8)
20. Temperature (°C) of the exhaust gas (Recorder Point #9 or #10)
21. Check point to verify the recorder readings

The data for the first ten items except for the time of day are entered by means of rotary switches on the console control unit and the remote control units. These points represent relatively constant numerical data and are introduced manually. Position change signals are received from a photo relay mounted in each respiration chamber. When an animal stands, it breaks a beam of light from a photo relay (Detect-O-Ray Model L-162C) and a contact closure is made. This is counted by a counter in the IBM and a timer is started, which continues to operate until the animal lies down.

The total volume of exhaust gas drawn from the respiration chamber is measured by counting the number of complete revolutions of the bellows shaft of each gas meter. A microswitch mounted on the bellows shaft of each meter produces the signal which is accumulated by a counter in the IBM, and for each six-minute period the total is printed and punched.

Items 15 through 21 are obtained by means of a 10 point, 3 range strip chart recording potentiometer (Modified Bristol Model 10RB570-T38X-T48-T17) with a Giannini Datex (14300 Series, No. C-109) Encoder, a Control Chassis (Datex K-154) and the appropriate sensing elements to measure temperature, barometric pressure and relative humidity. The shaft position of the recorder when a point is printing is measured by the Giannini Datex Encoder. The Encoder is coded over an angular travel of 336°, exactly corresponding to the full scale angular travel of the shaft. In this manner analog information is translated to a digital number presentation, in binary form. A control chassis translates the binary digits into a decimal digital readout, which is required for operation of the IBM card punch and typewriter. The resulting data is coded and printed as digits between 000 and 999. The points on the recording potentiometer and the variables measured are as follows:

1. Index point 505
2. Barometric pressure of the room (710 - 810 mm. Hg)
3. Relative humidity of chamber A (51-88% or 40-99%)
4. Relative humidity of chamber B (51-88% or 40-99%)
5. Relative humidity of exhaust gas from ventilation recording unit No. 1. Range varies with sensing element used as follows:

Hygrometer No.	Identifying Color	Range of Relative Humidity at 26.7°C
4-4816	Red	11-23%
4-4817	Orange	18-33%
4-4818	Yellow	26-42%
4-4819	Green	41-61%
4-4820	Blue	51-74%
4-4821	Violet	68-88%
4-4822	Gray	81-99%

6. Relative humidity of exhaust gas from ventilation recording unit No. 2 (Range varies with sensing element the same as on point #5)
7. Temperature of chamber A (15-25°C)
8. Temperature of chamber B (15-25°C)
9. Temperature of exhaust gas from ventilation recording unit No. 1. (15-25°C)
10. Temperature of exhaust gas from ventilation recording unit No. 2 (15-25°C)

A standard resistance is fixed in the recorder in the No. 1 position to act as an index point. This signal, when received by the IBM-APR, indicates whether the recording equipment is operating properly. If the value is between 500 and 509 a verifying X is printed and punched, but outside this range the values are printed in red and no X is punched into the card.

Barometric Pressure - The sensing element which measures the barometric pressure of the room is a Statham Pressure Transducer (Model No. PA11TCF-1.5-350), with a pressure range of 0 to 1.5 psi absolute. The range 710-780 mm. Hg was obtained by hanging a weight (1758 grams) to the strain sensitive resistance wire element to balance atmospheric pressure. The system is temperature compensated, thus eliminating the necessity of corrections for changes in temperature. Calibration was accomplished by comparing the recorded value with the atmospheric pressure measured with a mercurial barometer. Each mercurial barometer reading was corrected for temperature and gravity and then used in the calculation of a regression formula to convert the coded value to mm. Hg. A total of 199 values covering the observed range of 737.7-778.7 mm. Hg (368-936 coded value) during a six-month period were used to obtain the following formula: $Y_2 = 710.747 + 0.07275\ X$. Y_2 is the barometric pressure of the room in mm. Hg and X is the coded IBM value. This value is then used in the calculations to correct the gas volume to 760 mm. Hg, dry gas, 0°C.

Relative Humidity - Relative humidity measurements of the respiration chambers and exhaust gas are accomplished by means of Aminco-Dunmore Electric Hygrometer sensing elements. These elements consist of a polystyrene cylinder, a dual winding of palladium wire, a coating of moisture sensitive compound (lithium chloride) and plug-in contact pins. Limited range elements are used in the exhaust gas line, and they may be changed to obtain the proper range under a given set of conditions. The majority of the values obtained to date have fallen between 55 and 65% relative humidity, which could be measured by either the green (4-4819) or blue (4-4820) elements. It was found that the relative humidity of the respiration chambers was subject to much wider fluctuations, so dual and multiple sensing elements were installed in the chambers. The elements are similar in operation to those described for exhaust gas measurements except that the relative humidity range that can be measured is wider, being 51-88% for the dual element (Aminco No. 4-4776) and 40-99% relative humidity at 26.7°C for the multiple sensing element (Aminco No. 4-4785). The formula that is used to convert the coded data into per cent relative humidity varies with the element being used and the range being measured. Examples of formulae are as follows:

$$Y_{3\&4}\ (8593\ \&\ 8594\ \text{at}\ 26.7°C,\ 000\text{-}499) = 50.774 + 0.0304\ X$$
$$Y_{3\&4}\ (8593\ \&\ 8594\ \text{at}\ 26.7°C,\ 500\text{-}999) = 44.334 + 0.0467\ X$$
$$Y_{3\&4}\ (8605\ \&\ 8606\ \text{at}\ 26.7°C,\ 000\text{-}299) = 38.047 + 0.0296\ X$$
$$Y_{3\&4}\ (8605\ \&\ 8606\ \text{at}\ 26.7°C,\ 300\text{-}999) = 25.498 + 0.0749\ X$$
$$Y_5\ (G87198\ \text{at}\ 26.7°C,\ 000\text{-}699) = 40.826 + 0.01673\ X$$

Y_5 (G87198 at 26.7°C, 700-999) = 22.37 + 0.0408 X
Y_5 (B87772 at 26.7°C, 000-199) = 50.050 + 0.0315 X
Y_5 (B87772 at 26.7°C, 200-699) = 53.378 + 0.0148 X
Y_5 (B87772 at 26.7°C, 700-999) = 37.615 + 0.0360 X
Y_6 (G87199 at 26.7°C, 000-199) = 39.656 + 0.0121 X
Y_6 (G87199 at 26.7°C, 200-699) = 40.735 + 0.0159 X
Y_6 (G87199 at 26.7°C, 700-999) = 52.877 + 0.0352 X
Y_6 (B87773 at 26.7°C, 000-199) = 49.550 + 0.0315 X
Y_6 (B87773 at 26.7°C, 200-699) = 52.878 + 0.0148 X
Y_6 (B87773 at 26.7°C, 700-999) = 37.115 + 0.0360 X

In each of these formulae Y is per cent relative humidity at 26.7°C; X is the recorded coded value; the first subscript is the point number of the recorder; and the figures in the parentheses are the element identification, temperature, and coded value range for which the formula is most appropriate. Each relative humidity value thus obtained is corrected for temperature by multiplying 26.7 minus the appropriate temperature by the change in relative humidity per degree centigrade in that range and adding or subtracting it from the calculated Y. Aqueous vapor pressure may then be found by multiplying the per cent relative humidity by the mm. Hg vapor pressure at saturation at that temperature. Aqueous vapor pressure at saturation at different temperatures may be found in psychrometric tables (Zimmerman and Lavine, 1945; Carpenter, 1948; Swift and French, 1954) or may be calculated with a reasonable amount of accuracy using the following formula:

$$Y_{se} = 1.0951\ X - 4.101$$

Y_{se} is the aqueous vapor pressure at saturation in mm. Hg at X °C and X is the dry bulb temperature in °C. This formula was calculated from values obtained from tables of Zimmerman and Lavine (1945) within the ranges of 15.0 to 25.0°C and would not be appropriate outside this range. A curvilinear regression formula would give a slightly better fit than the linear value shown above, but the improvement in precision in this narrow range is somewhat doubtful.

Temperature - The sensing elements for measuring the temperature of the exhaust gas are nickel resistance thermometers with fittings for installation in the 1.5 inch pipe line connecting the two gas meters on each ventilation-recording unit. The temperature range is from 15 to 25°C, with each division on the recorder chart being equivalent to 0.1°C. Each element was calibrated by immersion in a circulating water bath and comparing the IBM readout with manual readings of the bath temperature using a mercury bulb thermometer. The thermometer was a Parr thermometer which had been used with the bomb calorimeter and could be read within 0.01°F. The elements were all found to be linear in the 15-25° range and regression formulae were calculated.

Y_9 (2426-B) = 15.004 + 0.0101 X
Y_{10} (2425-B) = 15.066 + 0.0100 X
Y is the temperature in °C and X is the IBM readout.

The chamber temperature elements could not be immersed in water, so they were calibrated by placing element 2425-B (Y_{10}) in each chamber for a period of several days during which time the temperatures were recorded continuously and the chamber interior heated with a circulation-type heater or cooled with a room air conditioner. The resulting formulae were as follows:

Y_7 (8593) = 15.197 + 0.0100 X
Y_8 (8594) = 15.159 + 0.0100 X
Y is the temperature of the chamber in °C and X is the IBM readout.

Data Readout - A signal from the IBM-APR system starts the recording potentiometer at the end of each six-minute period. The ten points are recorded, and the recorder idles until another signal is received. For each six-minute period, the recorder passes through two complete ten point cycles. Chamber A and the primary mobile test stand (ventilation recording unit No. 1) are recorded in the first pass, and Chamber B and the secondary stand (unit No. 2) are recorded in the second pass. Therefore, on the typewritten record on the first line points 1,2,3,5,7,9 are printed, which correspond to Chamber A and unit No. 1, and on the second line points 1,2,4,6,8,10 are recorded for Chamber B and ventilation recording unit No. 2.

The typewritten record is used for preliminary calculations and continuous check on the recording system. Most of the routine calculations, however, are made by an electronic data processing machine from the punched card data.

Summary - Automatic recording equipment for use with open-circuit respiration chambers, particularly in studies on the energy metabolism of dairy cattle, has been described. The instrumentation for measuring total gas flow, temperature, relative humidity, barometric pressure, animal position changes and related information has been developed to reduce the labor and time required to conduct respiration trials with large animals. The equipment consists of a strip chart multipoint recording potentiometer with a shaft position converter and translation unit to transmit data from sensing elements in digital form to an automatic typewriter and IBM card punch at regular predetermined intervals. A pressure transducer with a counter poise to balance atmospheric pressure is used to measure barometric pressure, the temperature is measured with nickel resistance bulbs, and relative humidity is determined with electric hygrometers. From coded data obtained by this means the total exhaust gas may be corrected to standard temperature and pressure (0°C, 760 mm. Hg, dry gas) by the use of an electronic computer.

Chamber No.	Time	Date	Oper. No.	Animal No.	Animal Wt.	Trial No.	Expt. No.	Position Changes	Time Standing	Gas Vol.	Gas Vol.	Index	Barom. Press.	Rel. Humdty. Chamber	Rel. Humdty. Exhaust	Temp. Chamber	Temp. Exhaust	Verification
2	07.81	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	664	000	021	246	554	X
3	07.90	04-21-59	1	0869	0613.5	11-905		0	59	023	023	511	666	019	077	556	501	
2	07.91	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	665	000	010	247	561	X
3	08.00	04-21-59	1	0869	0613.5	11-905		0	61	025	025	511	663	027	169	559	509	
2	08.01	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	664	000	021	219	565	X
3	08.10	04-21-59	1	0869	0613.5	11-905		0	52	023	024	504	667	000	050	556	503	X
2	08.11	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	666	000	045	211	562	X
3	08.20	04-21-59	1	0869	0613.5	11-905		0	59	023	023	504	668	000	030	548	497	X
2	08.21	04-21-59	1	0608	0551.2	11-905		0	00	008	007	505	666	000	045	217	556	X
3	08.30	04-21-59	1	0869	0613.5	11-905		1	61	024	024	504	669	000	069	571	503	X
2	08.31	04-21-59	1	0608	0551.2	11-905		0	00	008	009	505	669	000	047	167	562	X
3	08.40	04-21-59	1	0869	0613.5	11-905		0	60	024	024	509	668	011	215	575	519	X
2	08.41	04-21-59	1	0608	0551.2	11-905		0	00	008	007	505	667	000	046	150	574	X
3	08.50	04-21-59	1	0869	0613.5	11-905		0	59	024	024	444	666	015	062	580	523	
2	08.51	04-21-59	1	0608	0551.2	11-905		0	00	007	008	504	667	000	050	275	579	X
3	08.60	04-21-59	1	0869	0613.5	11-905		4	60	024	025	499	666	016	024	574	516	
2	08.61	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	666	000	050	286	576	X
3	08.70	04-21-59	1	0869	0613.5	11-905		0	60	024	024	505	666	016	017	575	522	X
2	08.71	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	667	000	044	303	581	X
3	08.80	04-21-59	1	0869	0613.5	11-905		0	59	025	024	511	665	014	170	578	529	
2	08.81	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	665	000	044	300	589	X
3	08.90	04-21-59	1	0869	0613.5	11-905		4	60	025	026	510	666	010	063	574	531	
2	08.91	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	666	000	045	263	589	X
3	09.00	04-21-59	1	0869	0613.5	11-905		0	60	024	024	504	666	006	032	567	524	X
2	09.01	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	667	000	044	263	586	X
3	09.10	04-21-59	1	0869	0613.5	11-905		0	59	024	024	504	670	001	015	570	530	X
2	09.11	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	668	000	042	292	589	X
3	09.20	04-21-59	1	0869	0613.5	11-905		0	61	026	026	506	668	002	106	574	535	X
2	09.21	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	671	000	038	286	595	X
3	09.30	04-21-59	1	0869	0613.5	11-905		0	60	024	025	506	668	003	062	572	538	X
2	09.31	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	669	000	039	272	598	X
3	09.40	04-21-59	1	0869	0613.5	11-905		3	59	023	023	516	668	000	028	567	532	
2	09.41	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	669	000	034	259	597	X
3	09.50	04-21-59	1	0869	0613.5	11-905		0	61	025	024	504	670	000	020	571	533	X
2	09.51	04-21-59	1	0608	0551.2	11-905		0	00	008	008	504	670	000	027	293	601	X
3	09.60	04-21-59	1	0869	0613.5	11-905		0	60	025	026	505	670	000	177	577	543	X
2	09.61	04-21-59	1	0608	0551.2	11-905		0	00	008	008	505	672	000	032	278	609	X
3	09.65	04-21-59	1	0869	0613.5	11-905		0	32	013	013	504	671	000	108	579	546	X
2	09.67	04-21-59	1	0608	0551.2	11-905		0	00	004	005	505	673	000	030	271	613	X
3	09.70	04-21-59	1	0869	0613.5	11-905		0	27	010	011	504	669	000	061	579	545	X
2	09.71	04-21-59	1	0608	0551.2	11-905		0	00	004	003	505	670	000	030	272	613	X
3	09.80	04-21-59	1	0869	0613.5	11-905		0	61	025	024	508	671	000	031	573	537	X

Example of data sheet from automatically recorded information collected during a respiration trial.

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